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14. ABSTRACT The finite element simulation of blast wave formation, wave interactions with the head and subsequent response in the brain to blast exposure various conditions were carried out. Based on Bowen's curve, the maximum peak pressure transmitted to the scalp, skull and brain were about 3, 12 and 4 times respectively higher than the blast pressure received by the head. Increasing levels of overpressure produced higher intracranial pressure and strain. In contrast, increasing levels of impulse had adverse effects on the brain pressure. A person in a prone head-on position subjected to the ground explosion would sustain a greater damage in the brain as compared to one standing in a free blast condition. The effects of being adjacent to a reflecting wall were noticeable only on the region of the brain closer to the wall. The blast threats based on Bowen iso-damage curve of short duration regimen do not always produce the same level of compressive stress responses in the brain. These variations in tissue response predict potential multi-level damage outcomes rather than the same level estimated using the blast input-based tolerance curve of Bowen.					
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## Introduction

Traumatic brain injury (TBI) is a signature injury of the recent wars, affecting a majority of the military casualties. The existing human injury tolerance to primary air blast is based on a function of the peak overpressure and positive pulse duration applied to the biological system. Despite the lack of injury tolerance data for the human brain, these injury functions do not account for the broad spectrum of frequencies and stress concentrations from shock wave propagation inside the head, and thus are insufficient for predicting regional brain dysfunction. Currently, the interaction of the blast wave with the head and subsequent transformation of various forms of shock energy internally have not been demonstrated in the human head. Up to now, the precise mechanisms of blast TBI are unknown. We hypothesize that primary blast TBI is directly induced by pressure differentials across the skull/fluid/soft tissue interfaces and is further reinforced by the reflected stress waves within the cranial cavity, leading to stress concentrations in certain regions of the brain. The objective is to characterize the effects of blast waves produced by various explosions on the resulting tissue level response of the brain using an anatomically inspired finite element (FE) model of human head combined with shock physics. The localized response parameters predicted by the head model will be analyzed and compared between various loading conditions. We hypothesize that the responses at the locations of major tracts and the brain areas they interconnect will be related to clinical symptoms and pathophysiological changes seen in blast TBI patients. The relationships between localized brain response (internal) parameters will be correlated with blast wave (external) parameters to delineate dose-effect mechanisms contributing to blast TBI. Once established, this cause-effect relationship for blast induced TBI will be of significance because it will link the actual head response to the shock effect on tissues within the brain. The information can be further used to develop injury assessment functions to assess the injury potential using instrumented manikins (human surrogates) in blast reenactment.

## Body

### *Aims and Tasks*

Specific Aim 1: To simulate blast wave generated by a variety of explosions in the free-field and near a reflector and to quantify overpressure and impulse as it interacts with the head at various orientations using a biomechanically-based finite element (FE) model of the human body and head.

- 1.1 Simulate the explosion and wave propagation of various intensities
- 1.2 Effect of the orientations of body/head axis to blast wind direction
- 1.3 Effect of the reflecting surface in various orientations

Specific Aim 2: To quantify the pattern of the shock wave as it travels through various structures of the head/brain and the resulting mechanical responses in various regions of the brain as predicted by an anatomically-detailed FE head model.

- 2.1 Internal responses predicted at each anatomical structure of the brain
- 2.2 Injury localization

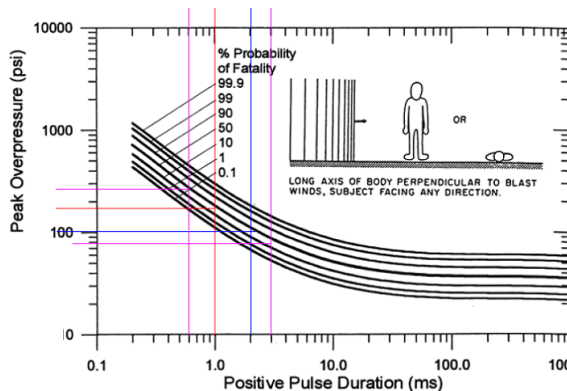
Specific Aim 3: To establish the relationships between brain tissue response parameters to external blast wave parameters to the head for various conditions in order to delineate the dose-effect mechanisms contributing to blast TBI.

- 3.1 Establish brain response as a function of shock wave striking the head

## Aims 1 and 2: Methods

### Blast Loading Determination (Task 1.1)

Four levels of overpressure on the pulse duration between 0.5 and 3 ms of the Bowen's iso-damage pressure-duration (10% lethality) curve were determined to simulate a range of blast loadings to the human head (Figure 1) (Bowen et al. 1968). The stand-off distance and the net weight of the explosive (TNT equivalence) needed to match four levels of overpressure and pulse duration were calculated using a scaling equation (Mays and Smith 1995). For near side of target, the incident pressure is expressed as  $P = 6.7/Z^3 + 1$  (in MPa) where  $Z = R/W^{1/3}$ ,  $R$  is the distance from the center of the charge in meters and  $W$  is the charge mass expressed in kilograms of spherical TNT. Table 1 lists the calculated weight of the spherical TNT explosive and the corresponding stand-off distance required to produce four blast wave profiles based on Bowen's iso-damage curve (Figure 1).



**Figure 1: Four blast peak overpressure and positive pulse duration profiles on Bowen's 10% lethality curve**

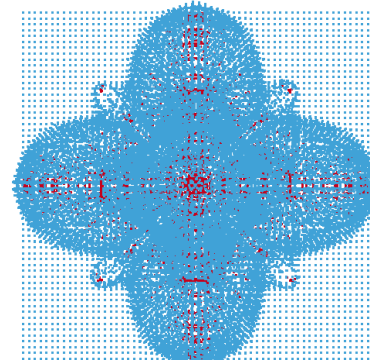
**Table 1: Calculated stand-off distance and TNT equivalent to match the blast effect - overpressure and positive pulse duration**

Case	Pressure (MPa)	Duration (ms)	TNT (kg)	Stand-off Distance (m)
1	1.40	0.6	1	0.8
2	1.20	1	2	1.1
3	0.60	2	5	1.9
4	0.49	3	10	2.5

### Numerical Approach (Task 1.1)

To simulate the wave formation and wave propagation, the Smooth Particles Hydrodynamics technique (SPH) was proposed as a potential numerical technique to achieve the goal. SPH is a meshless Lagrangian method which doesn't require grid for space discretization. Therefore, SPH model does not suffer from mesh tangling in large deformation problems. SPH is most often applied to astrophysical problems and problems involving large material deformation, e.g., high-speed impact of solid bodies (Johnson et al. 1994), chemical explosion (Liu et al. 2003) and explosive forming in industry (Meyers 1994). Despite the use of SPH method for a great variety of problems, little has been done relative to the 3-D problems due to high computational cost of the method resulting from the need for many particles.

The SPH method was applied in an attempt to simulate the TNT explosion and wave propagation in air. Based on Bowen's curve, Case 1 would be smallest model for 1 kg TNT and 0.8 meter standoff distance. To ensure the accuracy of the energy coupling at the SPH and Lagrangian interface, 4 particles on each contacting segment of Lagrangian element was considered. This setup yielded a total number of particles exceeding 5,000,000. The existing



**Figure 2: Explosion and expansion of a spherical TNT charge of 0.5 kg and wave propagation simulated by a SPH model at 0.13ms**

computational resource was not sufficient to handle the size of the model. By gradually reducing the model size and particles down to 1,500,000, a 0.5 kg TNT at 400 mm standoff distance model was simulated but was terminated prematurely at 0.13 ms after detonation (Figure 2). The incident pressure results at various distances from the center of the charge exhibited a typical triangular wave form. However, the peak overpressure was significantly under-predicted by the SPH model at 20% of the overpressure value (12 MPa) calculated by a cubic scale method (Mays and Smith 1995). This was due partially to instability of the numerical solution due to lack of sufficient numbers of SPH particles in space.

Due to solution accuracy and efficiency problems associated with SPH method, a thorough investigation of other numerical techniques was conducted with an emphasis placed on the methods that can solve the solution of multi-space discretization in a single modeling process and the capability of coupling and interaction of different numerical methods. The Multi-Material Arbitrary Lagrangian and Eulerian (MMALE), a mixture of Lagrangian and Eulerian methods, showed capabilities of modeling fluid and structural dynamics without suffering mesh distortion problems (Benson 1997). This method has been incorporated in LS-Dyna, an explicit nonlinear, large deformation, dynamic finite element solver (LSTC, Livermore, CA). The MMALE method has been utilized by many in the simulations of structural responses to blast loading (Benson 1997, Lu et al. 2006, Plotzitz et al. 2007, Zhang et al. 2008, Chafi et al. 2009, Borvik T et al. 2009, Slavik 2009). This ALE method was utilized to simulate blast wave phenomena, their interaction directly with FE human model and calculate the response in the brain.

#### FE models of High Explosive, Air, Soil (Task 1.1)

The FE models of a spherical TNT charge of 1, 2, 5, and 10 kg as determined in Table 1 were created with a radius of 52, 66, 91, and 112 mm, respectively. The FE models of the air occupied the volumetric space between the explosive and the head model and around the head. The non-reflecting symmetry boundary condition was applied to 1/4<sup>th</sup> of the TNT and air and nodal coupling was assured at the interfaces between the TNT and air mesh (Figure 3a). The explosives and air were modeled with multi-material ALE elements. The mesh programs used were Hypermesh (Altair, MI) and Morpher (DEP, CA). Finite element analysis was performed using LS-Dyna 971. In order to assure the accuracy of the solution yet save computational cost a mesh convergence study was performed first using 3 different mesh densities, 2.5, 5 and 10 mm, for the TNT and air models.

The detonation and expansion of the TNT explosive materials was described using the JWL (Jones-Wilkins-Lee) equation of state (EOS) along with a high explosive material definition (Dobratz 1981). The JWL equation is described as:

$$P = A \left( 1 - \frac{\omega}{R_1 V} \right) e^{-R_1 V} + B \left( 1 - \frac{\omega}{R_2 V} \right) e^{-R_2 V} + \frac{\omega E}{V}$$

Where  $V = \rho_0$  (initial density of an explosive)/ $\rho$  (density of detonation gas).  $E$  is specific internal energy.  $A$ ,  $B$ ,  $R_1$ ,  $R_2$ ,  $\omega$  are JWL fitting parameters (Table 2).

**Table 2: JWL and material parameters for TNT explosive**

$\rho_0$ (kg/mm <sup>3</sup> )	Detonation velocity (m/s)	CJ pressure (GPa)	Material constant(GPa)					Detonation energy/unit E0 (GPa)
			A	B	R1	R2	W	
0.63e-6	6930	27	374	3.21	4.15	0.95	0.3	7

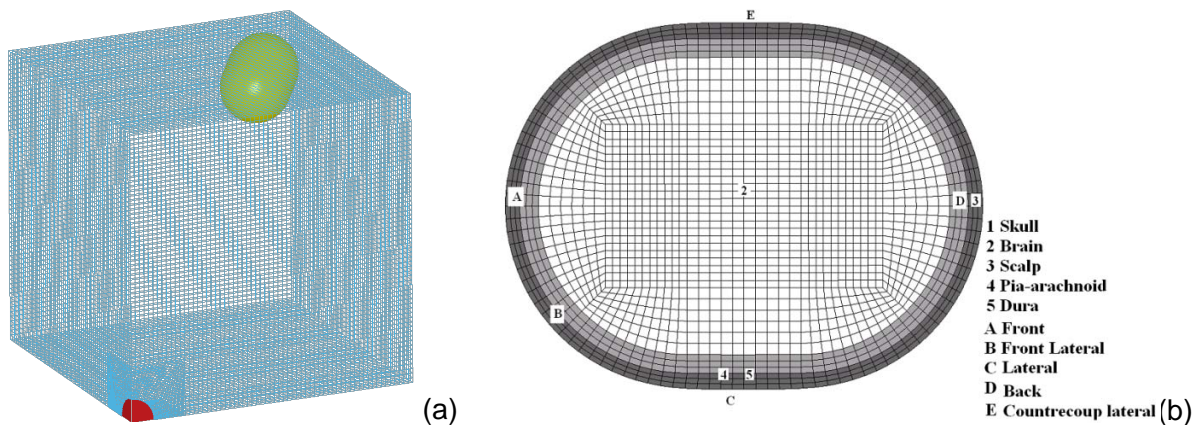
The air was simulated as a perfect gas using a linear polynomial equation of state (Wang 2001). The EOS is expressed in the following form:

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2) E$$

Where  $C_0 = C_1 = C_2 = C_3 = C_6 = 0$  and  $C_4 = C_5 = \gamma - 1$ ,  $\gamma$  is the ratio of specific heats and was defined to be 0.4. The initial internal energy/unit reference volume was  $2.5e-5$  GPa. The initial density was  $1.29e-9$  kg/mm<sup>3</sup>. No deviatoric strength was considered.

#### Head Model (Tasks 1.1-1.3)

The total numbers of elements used for different explosives and air models ranged from 500,000 to 1,300,000 depending on the cases. The sophisticated FE head model (WSUHIM) consists of over 330,000 elements. With the existing computational resources, the model system with integrated head, air, TNT and soil could not be successfully simulated. As a result, an idealized 3D human head model was developed and used first to understand the blast phenomena and interaction. The basic anatomical, geometrical information of this idealized head model was based on the sophisticated WSUHIM (Zhang et al. 2001, 2004a, 2004b, 2008). The head model consisted of the skin, scalp, layered skull, dura, pia mater and brain. The brain, skull and scalp were made of hexahedron solid elements, whereas the pia-arachnoid, dura and skin were made up of quadratic shell elements (Figure 3b). The mass of the model was measured to be 4 kg. The simplified model has the advantage of quantitatively discerning the mechanical mechanisms involved in wave transformation. With the recent acquisition of a new cluster system (128 processor and 16 GB RAM/node), it is now capable of simulating a blast event with 1,500,000-2,000,000 elements. The anatomically detailed WSUHIM is currently being integrated with the blast model in order to precisely capture the regional responses and allow the injury localization of mild TBI.



**Figure 3: a) Finite element models of TNT charge, air and head defined for air burst simulation, b) Idealized human head FE model with multiple locations defined for comparing pressure responses due to various blast loadings**

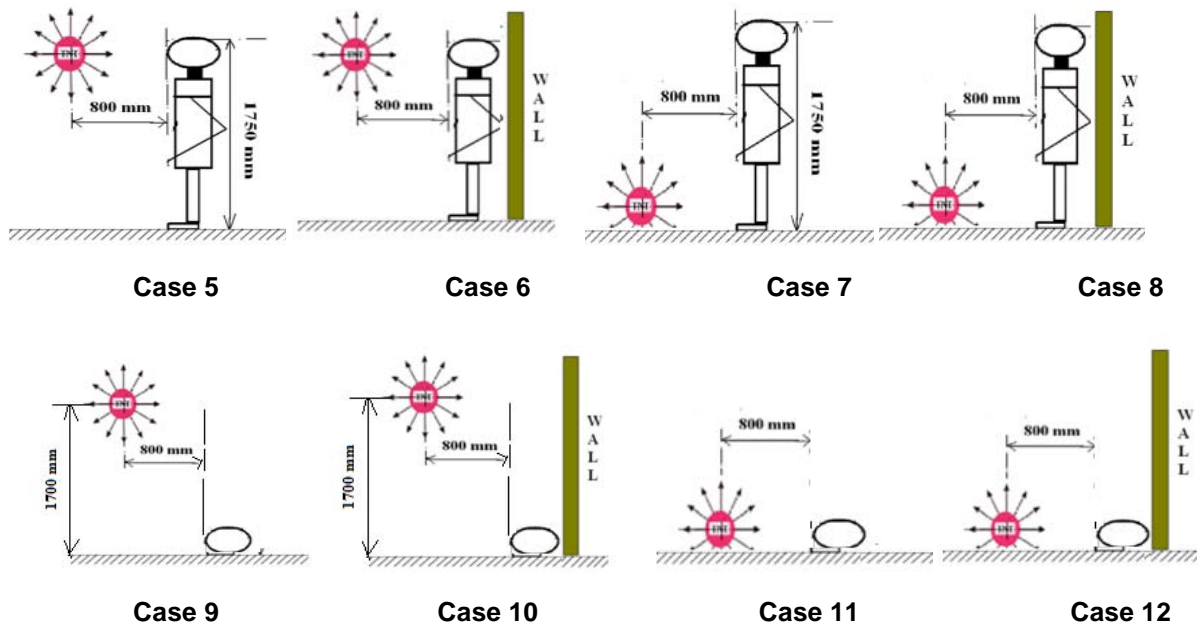
#### Effect of the Head/Body Position and Surrounds (Tasks 1.2, 1.3)

Free air explosion is defined here as an incident pressure of initial shock wave that does not interact with the ground before impinging on the target. Surface explosion simulates the blast environment where a charge is located on the ground and the blast pressure is reflected and emerged with air pressure before impacting the target. Upon blast striking the structure/head, the blast wave is being propagated through as well as being reflected from the object. The relative strengths of the reflected and transmitted shock waves depend upon the geometry,

material properties of the structure, and obviously the incident overpressure. The pressure reflected from the rigid surface can be more than 2 times the incident pressure and may interact with the blast wave in air and therefore reinforce it before impacting the structure. The following simulations were performed to compare the effect of explosion types, head/body positions and the presence of the reflecting wall on human head response to blast loading (Table 3). The blast level used for Case 1 of Bowen's curve (overpressure of 1.4 MPa and 0.6 ms positive duration) described above was used.

**Table 3: Simulation matrix to study the effect of the blast types, body positions and surrounds**

Case	TNT weight (kg)	Body Position	Blast Explosion	Surrounds	Stand-off Distance (m)
5	1	Standing	Free Air	Free	0.80
6				Wall	0.80
7			On the ground	Free	1.77
8				Wall	1.77
9		Lying	Free Air	Free	1.77
10				Wall	1.77
11			On the ground	Free	0.80
12				Wall	0.80



**Figure 4: The configuration of 8 blast conditions which simulate the subject at standing or lying positions with the head facing blast wave direction from the charge detonated either in air or on the ground. Cases 6, 8, 10 and 12 simulate the subject against a concrete wall (reflector) or free surrounds**

#### Effect of the Impulse (Addition)

For pulses of relatively short duration the response is dependent mostly on the impulse and for pulses of long duration the damage is dependent on the peak overpressure. To demonstrate the effect of changes in the impulse on the intracranial response, 1, 5, 10 kg weight of TNT explosives were used to produce the blast wave of identical overpressure from scaled distances. The simulations included the target in standing or lying position subjected to free air or ground explosion (Table 4). The brain pressure and head kinematics were compared between cases.

**Table 4: Simulation matrix on the effect of increased impulse of same overpressure level**

Case	TNT weight (kg)	Stand-off Distance (m)	Impulse (Pa-s)	Body/ Head position	Blast Explosion	Surrounds
13	1	0.80	190	Standing	Free Air	Free
14	5	1.37	330			
15	10	1.77	409			
16	1	0.80	190	Lying	On the ground	Free
17	5	1.37	330			
18	10	1.77	409			

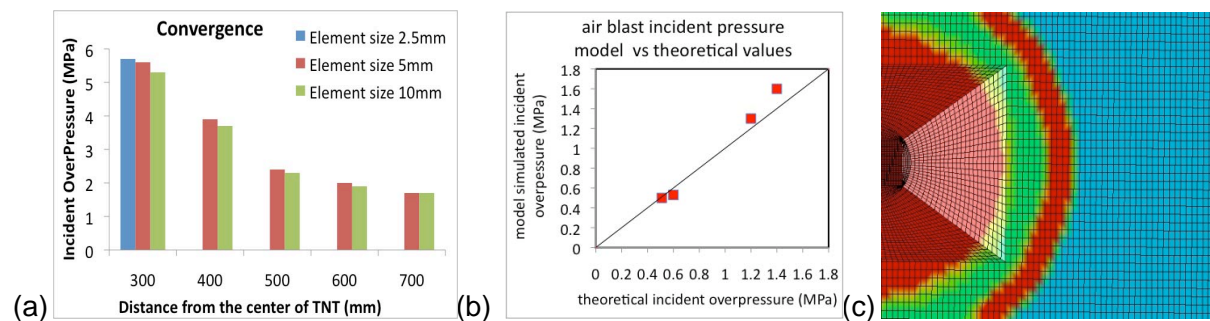
## Aims 1 and 2: Results and Findings

### Mesh Convergence (Task 1.1)

The incident pressure predicted by three element resolutions was compared (Figure 4a). The variability of pressure solution did not vary much from 2.5 mm to 5 mm obtained at 300 mm stand-off distance. Due to computational cost, other distances could not be simulated. Therefore the element size of 5 mm was believed to be adequate for capturing the blast wave phenomena yet at an affordable computational cost. With the new cluster system, 2.5 mm model will be simulated at larger stand-off distance to confirm the convergence of the model solution.

### Validation of Incident Pressure (Task 1.1)

The incident overpressure in the air before impacting the head was calculated by the models simulating 1, 2, 5 and 10 kg TNT detonation. The peak magnitudes were compared to the values calculated from the cubic scale law described above (Mays and Smith 1995) to verify the accuracy of the model results. The differences ranged from 2% to 14%. Figure 4b shows the validity of the simulated air blast incident pressures from various explosive intensities. The diagonal line denotes a perfect match between calculated and simulated results.

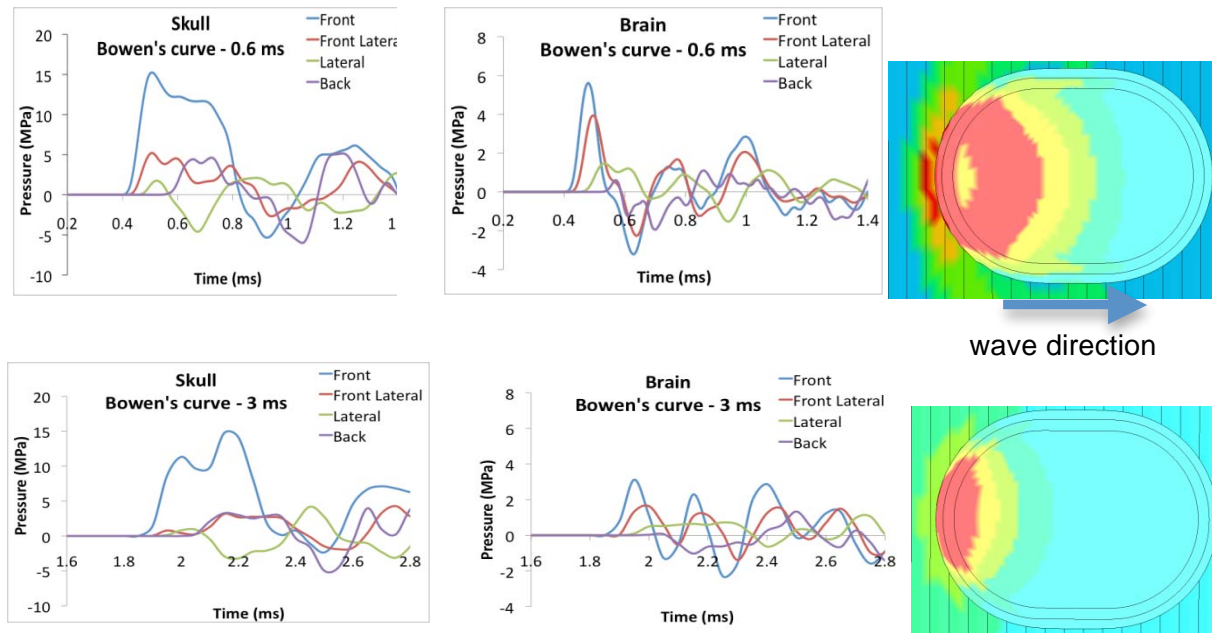


**Figure 4: (a) Mesh convergence results for blast pressure simulated using MMALE. (b) Validity of the blast incident pressure simulated using MMALE method, (c) blast wave propagation at 0.6 ms**

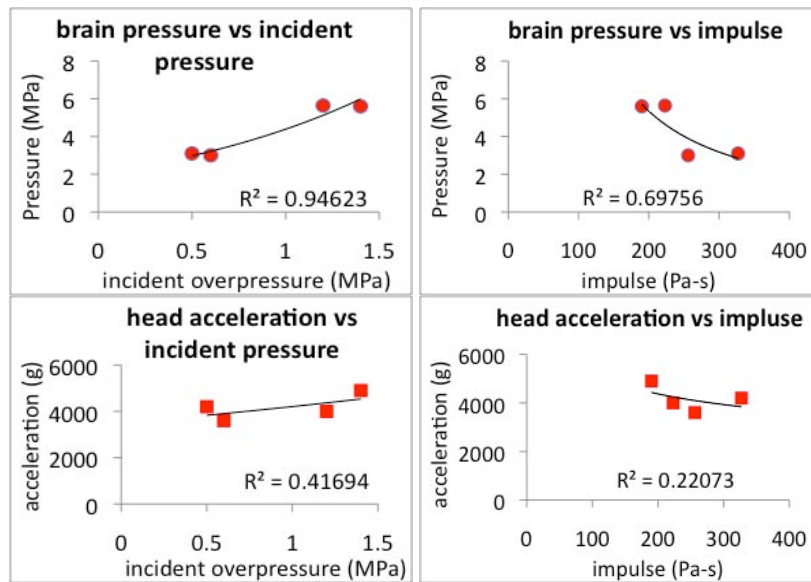
### Internal Brain Response to Blast Insult on Bowen's Curve (Tasks 1.1, 2.1)

Figure 5 shows the example pressure time histories and pressure wave contours predicted in the skull and brain from two of the four cases on Bowen's blast injury curve. The temporal and spatial pressure response patterns were similar between four cases. However, the level of intracranial responses resulting from blast threats based on the Bowen's iso- damage curve were significantly different at different values of peak overpressure and pulse duration. The brain pressure varied depending the region of the brain with the frontal brain where facing the oncoming blast wave had the maximum response (Figure 5). The pressure magnitude in the brain ranged from 3.0 to 5.6

MPa. The maximum peak pressure transmitted to the scalp, skull and brain were about 3, 12 and 4 times respectively higher than the blast pressure impacting on the surface of the head.



**Figure 5: Pressure time histories sustained by the skull and brain in response to the blast loading from Bowen's iso-damage curve**



**Figure 6: Intracranial pressure, head acceleration in relation to the overpressure and impulse taken between 0.6 and 3 ms duration of Bowen's tolerance curve.**

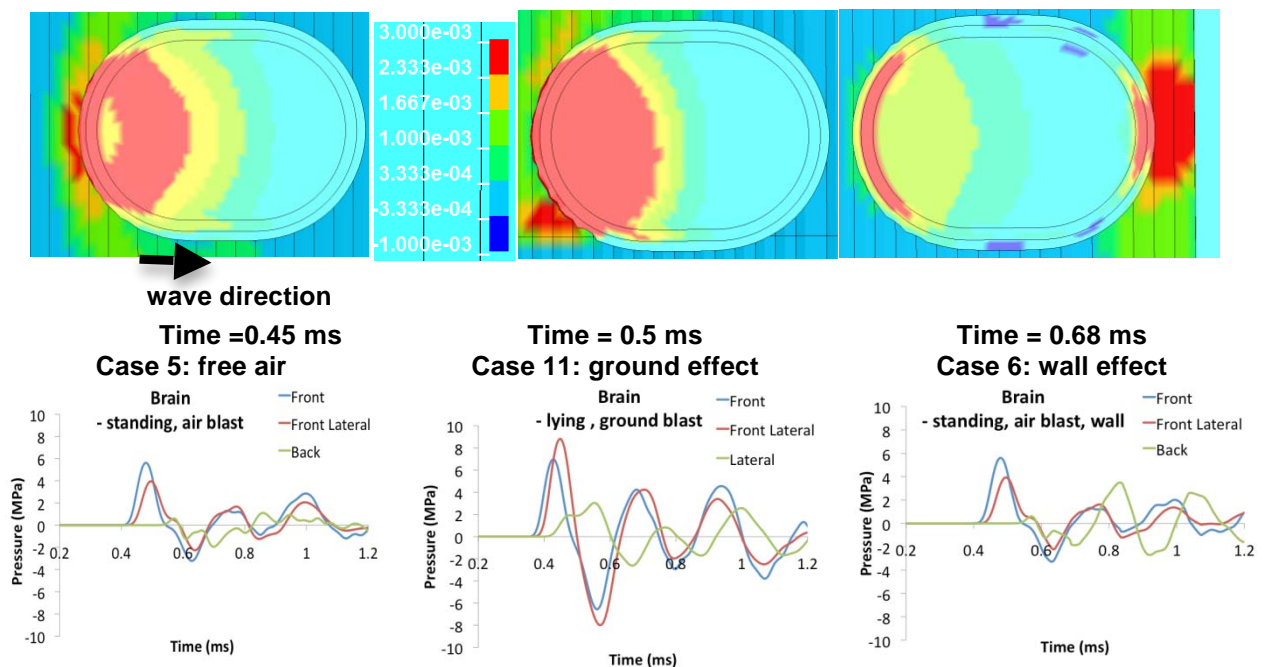
Regression analysis using power and exponential curve fitting was performed to correlate the response parameters (brain pressure and head kinematics) with input blast parameters (overpressure and impulse). As shown in Figure 6, the responses in the skull and brain

increased with increases in incident overpressure ( $R^2=0.946$ ) but decreased with increases in impulse ( $R^2=0.697$ ). The damage effect on the brain due to blast injury should take into account both overpressure and impulse. Similar trends but a weaker correlation was found for the head acceleration in relation to the overpressure ( $R^2=0.416$ ) and impulse ( $R^2=0.220$ ). Collectively, the results suggested that the blast wave could synergistically effect the head acceleration and level of the stress wave in the brain.

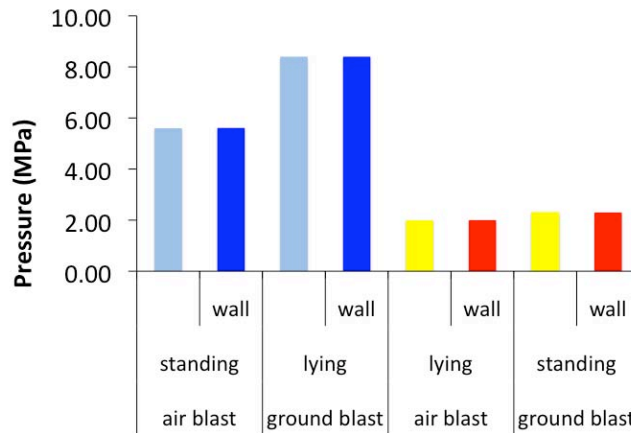
#### Effect of the Head Position, Surrounds on Brain Response (Tasks 1.2, 1.3, 2.1, 2.2)

A complex overpressure prior to striking the head was observed just above the ground for Case 11. This reflected wave interacting with the air blast peaked at about 1.25 times greater than the blast overpressure (1.4-1.6 MPa) produced from a free air blast (Case 1) (Figure 7). As a consequence, this increased total pressure resulted in an increased peak pressure response in the scalp, skull and brain by 19, 14 and 40%, respectively (Figure 8). This effect appeared to be less significant when the blast exposure dropped to a lower dose (220 kPa) (Cases 7 and 9) (Figure 8).

The presence of the concrete wall (reflected plate) on the back of the head influenced the pressure response on the posterior region of the head with the pressure increased from 1.8 MPa to 3.5 MPa at corresponding regions (Case 6) (Figure 7). However, the increased peak pressure in the occipital lobe did not exceed the maximum pressure occurring in the frontal and frontal lateral region of the brain, which were the regions facing the oncoming blast wave.



**Figure 7: The reflected pressure from the ground and the back wall affected the magnitude of the stress wave inside brain. The maximum pressure was located in the region facing oncoming blast wave as well the region where the reflected wave interacts with the incident pressure**



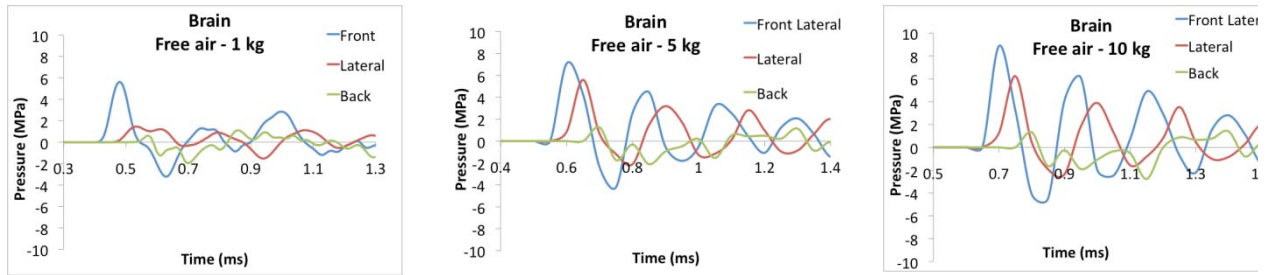
**Figure 8: The effect of the explosion types, head positions and with/without reflecting wall on the compressive stress response in the brain due to blast loading with overpressure of 1.4 MPa and 0.6 ms positive duration**

#### Brain Response to Blast Pressure of Various Impulses (Tasks 1,1, 1.3, 3.1)

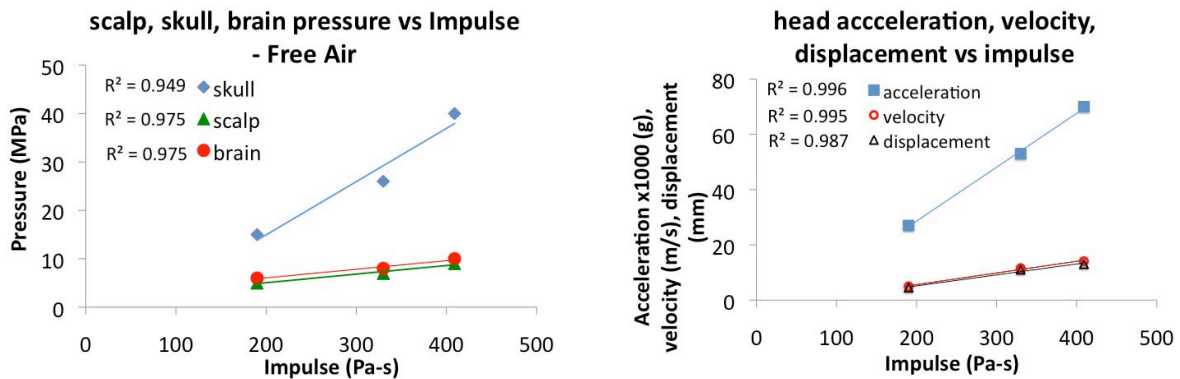
The overall responses in the scalp, skull and brain increased with increases in TNT weight from 1 to 5 to 10 kg even though the peak overpressure remained the same. The pressure magnitude in the scalp, skull and brain increased about 36, 72, and 33%, respectively when the explosive weight increased from 1 kg to 5 kg. Further increases in pressure were found at the corresponding structures by 28, 54, and 28% as the explosive increased from 5 kg to 10 kg. Figure 9 shows the histories of brain pressure response induced by the 1, 5, 10 kg TNT detonated at scaled distances.

The principal strain and maximum shear strain were found to be very less at only about 1% in the brain. However, the peak strain magnitude was increased as the duration of the blast increased. The use of higher explosive weights incurred the concomitant increases in head acceleration, velocity and displacement. The acceleration, velocity and displacement of the head were 4.4 mm, 5.6 m/s and 2700 g from 1 kg blast. These values increased by 90, 121 and 140% when increased to 5 kg and by 32, 22 and 18% when increased to 10 kg from 5 kg.

The linear regression analysis demonstrated that the tissue pressure response and the head kinematics were positively correlated with impulse whereas the overpressure was the same (Figure 10). This correlation implied that for a relatively short duration blast (0.5 - 3 ms) the damage effect to the brain components was dependent on impulse, which represents the momentum transfer to the body/tissue. This observation is consistent with wave phenomena observed for other structures. As shown in this study, when the duration of blast <3 ms is relatively shorter compared with the natural period of the oscillation of the head (4-10 ms), the loading is partially absorbed by the inertia thus resulting in a reduced structural deformation (Cullis 2001). The lesser brain strain deformation resulted from short duration shock loading was also reported by other researchers based on modal and temporal analysis (Gurdjian et al. 1970, Willinger et al. 1995, Ruan and Prasad 1996). The head model response presented here appeared to be consistent with what has been reported in literature. The modeling of the longer duration blast wave on the Bowen's curve would help discern the actual response or damage mechanism of the brain to a variety of blast overpressures and durations.

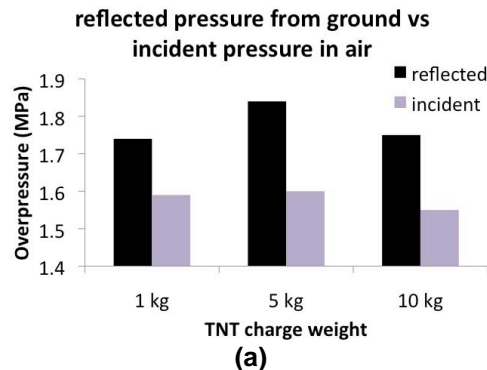


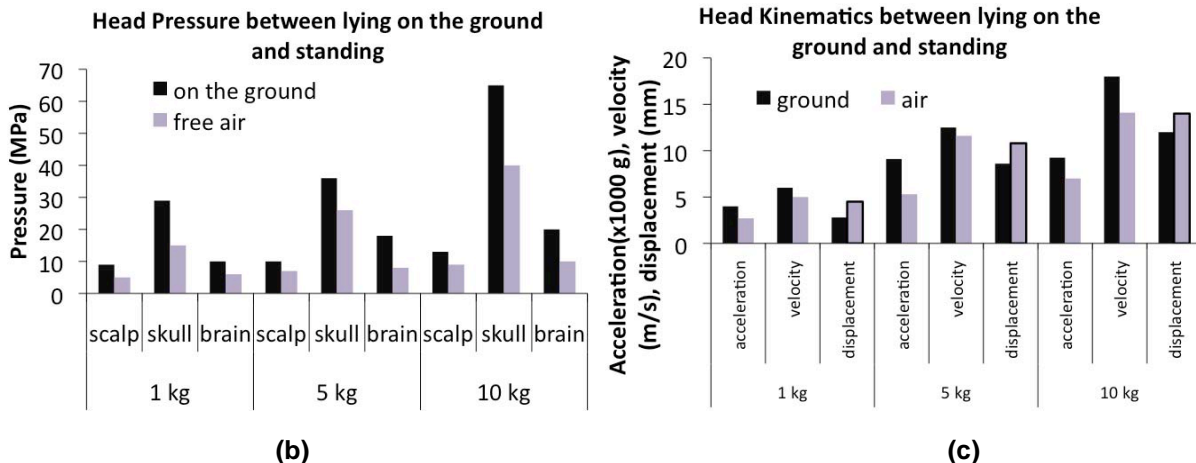
**Figure 9: Pressure time histories predicted in various regions of the brain from blast waves produced by 1, 5 and 10 kg TNT.**



**Figure 10: The responses of intracranial pressure, brain tissue strain, head acceleration, velocity and displacement strongly correlate to the increases in impulse at same level of blast overpressure as shown by linear regression.**

In cases of the ground explosion (Cases 16, 17, 18), the reflected blast pressure was about 1.25 times incident pressure produced by a free air explosion (Figure 11a). By the time the pressure coupled into the scalp, skull and brain structures, the stress wave was enhanced by a factor of 1.4 to 2.1 (Figure 11b). This trend was noticeably higher (1.7 times) for brain than for skull and scalp and become even greater as the impulse increased (2.1 at 10 kg). Similarly, the head acceleration and velocity also increased greatly compared with those due to air blast loading (Cases 13,14,15). Except for the head excursion, the displaced head was about 12 - 32% lower compared to that from a standing position (Figure 11c). This later observation was likely related to the frictional force between the soft scalp material and the ground surface.





**Figure 11: Comparison of pressure response (a) between the reflected and incident overpressure from ground and free air explosion, (b) at various structures of head, and (c) resulting head motion between ground and air explosion.**

### ***Ongoing and Future work***

As mentioned earlier, the acquisition of a High Performance Cluster will provide sufficient computational resource needed to accomplish the proposed work. Currently, the detailed high resolution FE model of human head is being integrated with the blast model using MMALE approach. This anatomically-detailed model will allow us to quantify internal responses predicted at each anatomical structure of the brain. The tasks specified under Specific Aim 2 will be completed. Particularly, the other mechanical quantities including the strain rate and stress/pressure rate will be examined and analyzed to determine the underlying biomechanical mechanisms of blast injury.

Finally, based on the results generated from Specific Aim 2 and 3 the relationships between the brain responses of various forms and the effective overpressure impacting on the head will be established. The injury predictors describing the cause and effect of blast injury will be determined by correlating the response parameters to the injury locations and to the clinical symptoms of TBI. This correlation will lead to the determination of dose-effect relationships describing the tissue damage effect operant in blast injury.

Once tissue damage thresholds have been determined from animal studies and translated to human brain tissue, the head model can be used for computer-aided design of safer environments and head-protection equipment to prevent blast injury.

### **Key Research Accomplishments**

- Smoothed Particle Hydrodynamics (SPH) simulations experienced accuracy and efficiency problems due to the need of high computational cost.
- Finite element models using a hybrid Lagrangian-Eulerian coupled with a Lagrangian approach appear to be useful tools for simulating blast wave phenomena and the head response due to blast loads. The validity of the blast pressure results was confirmed with that of calculated from the cubic scaling law.
- The level of intracranial responses resulting from blast threats based on the Bowen's iso-damage curve at 10% lethality were significantly different at different values of peak

overpressure and pulse duration. This implies that different levels of injury would be estimated at different points along this curve if the tissue stress is used as an injury predictor of blast TBI.

- Based on Bowen's curve, the maximum peak pressure transmitted to the scalp, skull and brain were about 3, 12 and 4 times respectively higher than the blast pressure received by the head. Increasing levels of blast overpressure produced higher intracranial pressure and principal strain. In addition, increasing levels of impulse had adverse effects on the brain pressure. Both overpressure and impulse effect contributed to the brain damage and their synergistic relation needs to be determined in future studies.
- In case of the body prone head-on to the surface blast, the blast wave reflected by the ground greatly contributed to increased pressure response by about 40% in the brain. The effect on brain pressure appears to be of less significance at a lower blast dose.
- The reflected pressure from the concrete wall (reflected plate) posterior to the head increased the pressure in the posterior region of the head by about a factor of 2. However, the frontal brain region facing the oncoming blast wind sustained the greatest response in pressure.
- At the same blast overpressure, increasing levels of impulse resulted from explosives significantly induced higher tissue stress waves in the brain as well as greater head acceleration, velocity and displacement. The results suggested that for a relatively short duration blast (0.5 - 3 ms) the damage effect to the brain component was strongly dependent on impulse, which represents the momentum transfer to the body/tissue.
- The blast wave reflected by the ground (by 1.25 factor) greatly contributed to increased pressure responses and head acceleration. However, the head displacement was restricted by the ground friction on a subject in a prone position.

## **Reportable Outcomes**

### Abstracts:

Zhang L. Biomechanical Mechanisms of Blast Induced Traumatic Brain Injury – Computational Modeling of Blast Impact and Brain Response. In 2009 Military Health Research Forum Conference Proceedings, Kansas City, Missouri, September 3, 2009.

Zhang L. Sharma S. Biomechanical Analysis of Blast Induced Brain Injury – Finite Element Modeling of Blast Effect on Mechanical Response of the Human Head. In Eighth World Congress on Brain Injury, Washington DC, March 10-14, 2010.

### Presentations:

Zhang L. Modeling of Biomechanical Response of Blast Induced Traumatic Brain Injury. Presented at 2009 Military Health Research Forum Conference, Kansas City, Missouri, September 3, 2009.

### Grant submitted based partially on the current work:

Co-PI of the grant proposal "PREVENTION OF BLAST-RELATED INJURIES" submitted to the U.S. Army Medical Research and Materiel Command (USAMRMC) in response to BAA 08-1.

## Conclusions

The ultimate goal of this research is to determine tissue level injury thresholds based on dose-effect relationships that utilize an improved understanding of tissue damage mechanisms operant in blast-induced traumatic brain injury. Collectively, the threshold information defined will enable the biomechanical head model to be used as a design tool to develop more effective helmets for soldiers.

The blast wave phenomena produced by various blast exposures and wave interactions with the head and subsequent transformation of shock energy internally in the head have been successfully simulated and analyzed using finite element modeling techniques. The following conclusions can be drawn based on the preliminary investigation:

- The blast threats based on Bowen iso-damage curve of short duration regimen for 10% lethality do not always produce the same level of compressive stress responses in the brain. These variations in tissue response predict potential multi-level damage outcomes rather than the same level estimated using the blast input-based tolerance curve of Bowen. However, this preliminary conclusion requires further investigation and more data to support the modeling results. Perhaps a tolerance curve determined specifically for neurotrauma is required.
- A person in a prone head-on position subjected to the ground explosion would sustain a greater damage in the brain as compared to one standing in a free blast condition.
- The effects of being adjacent to a reflecting wall are noticeable only on the region of the brain closer to the wall. The overall peak responses are dominated by the effect of the blast wave front on the regions of brain facing the blast wave.
- Head kinematics induced by blast loading increased significantly with impulse magnitude. The response values are of several orders greater than the threshold used in automotive safety standards.

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